

COST AND PERFORMANCE REPORT

Permeable Reactive Barriers Interim Summary Report: Permeable Reactive Barriers Using a Funnel and Gate Configuration

May 2002

Introduction

The report provides an interim summary of 14 projects (seven full-scale and seven pilot-scale) using permeable reactive barriers (PRBs) with a funnel and gate configuration composed of various reactive media to treat contaminated groundwater. A PRB contains or creates a reactive treatment zone oriented to intercept and remediate a contaminant plume. Contaminants are removed from the groundwater flow system by physical, biological, or chemical processes (EPA, 2002a).

Table 1 summarizes available information about the 14 projects, including year of installation, specific contaminants treated, PRB configuration and wall dimensions, installation method, installation depth, reactive media used, and cost data. Each of the PRBs was installed between 1995 and 2000.

Information on all fourteen projects was obtained from *Installation Profiles* published by the Remediation Technologies Development Forum¹ (RTDF) and which are available online at <www.rtdf.org>. The fourteen projects are:

Full-Scale Applications – Chlorinated Volatile Organic Compound (VOC) Contaminants

- Aircraft Maintenance Facility – *Southern Oregon, Oregon*
- Federal Highway Administration Facility – *Lakewood, Colorado*
- Former Manufacturing Site – *Seattle Washington*
- Industrial Site – *Coffeyville Kansas*
- Intersil Semiconductor Site – *Sunnyvale, California*
- Vapokon Petrochemical Work – *Søndersø, Denmark*

Pilot-Scale Applications – Chlorinated VOC Contaminants

- Alameda Point – *Alameda, California*
- Area 5, Dover Air Force Base (AFB) – *Dover, Delaware*
- Lowry AFB – *Denver, Colorado*
- Moffett Federal Airfield – *Mountain View, California*

Full-Scale Applications – Other Contaminants

- Former Mill Site – *Monticello, Utah*

¹ The RTDF has an ongoing effort to track PRB projects in the field and to periodically update information about those projects. When the case study was prepared, RTDF had published *Installation Profiles* for 47 PRB projects. The RTDF selects PRB projects for its web site based on availability of information, and includes mostly sites that have been in the field for relatively longer periods of time, as well as sites with relatively greater amounts of information. While not a representative sample of sites, the projects tracked by the RTDF provide a cross-section of the general types of projects in which PRBs had been installed. In addition, the RTDF is performing a longer-term review of project performance, and the data available for the case study is a snapshot of data available to date.

Pilot-Scale Applications – Other Contaminants

- East Garrington – *Alberta, Canada*
- Fry Canyon Site – *Fry Canyon, Utah*
- Y-12 Site, Oak Ridge National Laboratory – *Oak Ridge, Tennessee*

Summary of PRB Projects Using a Funnel and Gate Configuration

Contaminants Treated

Ten of the PRBs were used to treat groundwater contaminated primarily with chlorinated VOCs, including tetrachloroethene (PCE), trichloroethene (TCE), trichloroethane (TCA), dichloroethene (DCE), dichloroethane (DCA), dichloromethane (DCM), vinyl chloride (VC), and Freon®. The remaining four PRBs were used to treat other contaminants, such as uranium (U), arsenic (As), manganese (Mn), selenium (Se), technetium (Tc), vanadium (V), and organic contaminants, such as benzene, toluene, ethylbenzene, and xylene (BTEX).

PRB Configuration

All the projects included in this report employed a funnel and gate configuration. The funnel and gate PRB configuration involves the use of engineered subsurface barriers to capture and route groundwater flow through one or more gates, where treatment occurs. In most cases, funnels are comprised of sheet piling or slurry cutoff walls. However, engineered preferential groundwater flow pathways employing channels (sometimes referred to as “trench and gate” systems) also have been used to route groundwater flow to a reactive gate. At the Former Manufacturing Site in Seattle, Washington, the funnel and gate PRB configuration was selected to accommodate the buildings, railroad tracks, and public walkways on site, as well as adjacent public areas and properties, all of which precluded use of other PRB configurations or remediation technologies that would require a larger area to be excavated. Twelve PRBs employed low permeability “wing walls” to route groundwater to one or more reactive gates, which ranged in length from 6 feet at Moffett Federal Airfield, to 100 feet at the Former Mill Site in Seattle. Eight projects employed one reactive gate, while more than one gate were in use at six projects. The overall length of the funnel and gate PRBs ranged from 20 feet at Moffett Federal Airfield to more than 1,000 feet at the Federal Highway Administration Facility in Lakewood, Colorado. Figure 1 is a schematic of a PRB using a funnel and gate. No projects used a continuous reactive wall configuration, which is designed to intercept and treat the flow of contaminated groundwater without affecting groundwater flow, or a reaction vessel configuration where groundwater is routed through natural or engineered preferential pathways to a subsurface treatment zone.

PRB Installation Method

Of the 14 PRBs, nine were installed using supported excavation technologies such as slurries, sheet piling, shoring techniques, and trench boxes used to hold the excavation open during construction. The PRB at Moffett Federal Airfield was installed using a continuous trenching technology that allowed for simultaneous trench excavation and media placement. The PRB constructed at the Aircraft Maintenance Facility in Southern Oregon used a combination of

continuous trenching and supported excavation techniques. Three PRBs (the Coffeyville Industrial Site, the Intersil Semiconductor Site, and the Fry Canyon Site) did not specify the installation method used. None of the projects used unsupported excavation techniques or direct placement technologies, such as injection, *in situ* soil mixing, vibrated I-beam, hydraulic fracturing, jetting, and mandrel (H-beam).

PRB Installation Depth

The 14 PRBs were installed to depths ranging from 4 feet below ground surface (bgs) at the Fry Canyon Site to 45 feet bgs in the Area 5 site at Dover AFB. Three PRBs (the Former Manufacturing site, the Dover AFB site, and the Former Mill Site) were keyed into an underlying aquitard, such as claystone or bedrock. The PRB at the Federal Highway Administration Facility was not keyed into an impermeable layer due to the presence of fractured aquitard material. Information was not provided about whether the remaining 10 PRBs were keyed into an underlying aquitard.

Reactive Media Used

Iron, one of the most common reactive media used in PRBs (U.S. Air Force Research Laboratory, 2000), was used as a reactive media, either alone or in combination with a bulking agent or other reactive media (such as oxygen, amorphous ferric oxide (AFO), or phosphate (PO_4)), at 13 of the 14 PRBs. The pilot-scale PRB at the Fry Canyon Site evaluated three PRB gates composed separately of PO_4 , AFO, and iron to determine whether each could be used to treat groundwater contaminated with uranium. The East Garrington PRB used oxygen to strip contaminants from the groundwater and enhance biodegradation processes by aerating the reactive gate to treat BTEX in groundwater.

Project Performance

Five of the seven full-scale PRBs with performance data met, or were meeting their performance goals. Five sites (Former Manufacturing Site, Industrial Site, Intersil Semiconductor Site, Vapokon Petrochemical Works, and the Former Mill Site) at which PRBs were used to treat chlorinated VOCs reduced concentrations of individual contaminants from a high of 50,000 $\mu\text{g/L}$ to concentrations below maximum contaminant levels (MCL) or other site-specific cleanup levels. The Federal Highway Administration Facility, which had cleanup goals of 5 $\mu\text{g/L}$ for both TCE and 1,1-DCE, met the goal for TCE but effluent from the wall contained 1,1-DCE at concentrations up to 8 $\mu\text{g/L}$. The PRB at the Former Mill Site reduced concentrations of U, Se, Mn, V, and As to levels below site-specific cleanup goals.

Table 2 lists the primary contaminants at each site, as well as available information regarding influent and effluent concentrations and cleanup goals. The percent reduction is listed as “reported percent reduction” provided in the profile. In cases where influent and effluent concentration data were available but no percent reduction was reported, it was calculated and included in Table 2 as “calculated % reduction”.

Performance data also were provided for five of the seven pilot-scale PRBs included in the report, but either represent activity conducted over a shorter period of time or for a smaller area, and are not summarized here. However, the results, where available, are also provided in Table 2.

Table 2

**Permeable Reactive Barriers Using a Funnel and Gate Configuration to Treat
Contaminated Groundwater
Summary of Project Performance**

Summary of Project Performance at PRB Sites Using a Funnel and Gate Configuration						
Project	Contaminant	Influent Concentration (µg/L)	Effluent Concentration (µg/L)	Cleanup Goal (µg/L)	Reported % Reduction	Calculated % Reduction
Full-Scale Projects						
Aircraft Maintenance Facility	Total VOCs	500	NP	NP	NP	NP
Federal Highway Administration Facility	TCA	NP	<5	NP	NP	NP
	1,1-DCE	700	8	5	NP	>99%
	TCE	700	<5	5	NP	>99%
	cis-DCE	NP	<5	NP	NP	NP
Former Manufacturing Site	PCE	50,000	NP	4.2	99%	NP
	TCE	23,000	NP	56	99%	NP
	cis-DCE	8,000	NP	80	65%	NP
	VC	80	NP	2.9	95%	NP
Industrial Site	TCE	400	NP	NP	NP	NP
	1,1,1-TCA	100	NP	NP	NP	NP
Intersil Semiconductor Site	TCE	200	<5	5	NP	>97%
	cis-DCE	1,000	<6	6	NP	>99%
	VC	500	<0.5	0.5	NP	>99%
	Freon 113	60	NP	1,200	NP	NP
Vapokon Petrochemical Works	PCE	NP	<10	10	NP	NP
	TCE	NP	<10	10	NP	NP
	TCA	NP	<10	10	NP	NP
	DCA	NP	<10	10	NP	NP
	DCE	NP	<10	10	NP	NP
	DCM	NP	<10	10	NP	NP
	BTEX	NP	<10	10	NP	NP
Former Mill Site	U	700	ND	NP	NP	NP
	Se	40	ND	NP	NP	NP
	V	400	ND	NP	NP	NP
	Mn	10	NP	NP	NP	NP
	As	NP	ND	NP	NP	NP
Pilot-Scale Applications						
Alameda Point	cis-DCE	NP	136	NP	30%	NP
	VC	NP	217	NP	66%	NP
	TCE	>100	NP	NP	>91%	NP
	BTEX	NP	NP	NP	NP	NP
Area 5, Dover AFB	PCE	5,617	ND	NP	NP	NP
	TCE	549	ND	NP	NP	NP
	DCE	529	ND	NP	NP	NP
Lowry AFB	TCE	1,400	ND	NP	NP	NP
Moffett Federal	TCE	2,990	ND	NP	NP	NP

Summary of Project Performance at PRB Sites Using a Funnel and Gate Configuration						
Project	Contaminant	Influent Concentration (µg/L)	Effluent Concentration (µg/L)	Cleanup Goal (µg/L)	Reported % Reduction	Calculated % Reduction
Airfield	1,2-DCE	280	ND	NP	NP	NP
	PCE	26	ND	NP	NP	NP
East Garrington	BTEX	NP	<10	NP	NP	NP
Fry Canyon	U	20,700	NP	NP	>99%	NP

NP = Not Provided

Project Cost

Cost information was available for 13 of the 14 projects included in the report. No information concerning PRB operation and maintenance costs was provided for any site. Design costs ranged from \$30,000 to \$240,000 per site for four of the sites (Former Manufacturing Facility, Vapokon Petrochemical Work, Moffett Federal Airfield, and Fry Canyon Site). The installation cost per site (excluding design costs when provided) ranged from \$67,200 for East Garrington to \$1 million for three sites: Federal Highway Administration Facility, the Intersil Semiconductor, and Y-12.

Unit costs were calculated for five full-scale PRB applications (Aircraft Maintenance Facility, Federal Highway Administration Facility, Former Manufacturing Site, Industrial Site, Vapokon Petrochemical Work). Each of those PRBs was used to treat groundwater contaminated with chlorinated VOCs. The table below summarizes unit costs calculated using total project cost (excluding remedial design costs when reported) based on the length of wall constructed (\$ per linear foot) and the area (length times maximum depth) of wall constructed (\$ per square foot). No cost adjustments were made to normalize project costs in relation to the date when costs were incurred or the geographic location of the project.

Table 3

Permeable Reactive Barriers Using a Funnel and Gate Configuration to Treat Contaminated Groundwater Summary of Unit Costs

Summary of Unit Costs for PRB Sites Using a Funnel and Gate Configuration					
Project	PRB Length (Feet)	PRB Maximum Depth (Feet)	Project Cost (Excluding Design)	\$ per Linear Foot	\$ per Square Foot
Aircraft Maintenance Facility	750	34	\$ 600,000	\$ 800	\$ 24
Federal Highway Administration Facility	1,200	Not provided	\$ 1,000,000	\$ 833	Not calculated
Former Manufacturing Site	420	34	\$ 300,000	\$ 714	\$ 21
Industrial Site	1,000	30	\$ 400,000	\$ 400	\$ 13
Vapokon Petrochemical Work	450	30	\$ 700,000	\$ 1,556	\$ 52

Based on the available cost data, no clear trends in unit costs based on length or depth of the PRBs are evident. Table 4 summarizes the matrix characteristics and operating parameters for the fourteen projects that may have affected cost and performance for the PRB applications.

Table 4

**Permeable Reactive Barriers Using a Funnel and Gate Configuration to Treat
Contaminated Groundwater
Operating Parameters**

Operating Parameters	
Parameter	Range of Values
Soil Classification:	Varied (provided for all sites)
Clay Content and/or Particle Size Distribution:	Not provided
pH:	Up to 12 (Former Manufacturing Site)
Porosity:	Not provided
Depth Below Ground Surface or Thickness of Zone of Interest:	4 feet to 45 feet bgs
Total Organic Carbon:	Not provided
Presence of Nonaqueous-Phase Liquids:	Not provided
Groundwater Flow Rate:	0.1 ft/day to 18 ft/day
Type of Reactive Media:	Varied (Iron, Oxygen, AFO, PO ₄)

Lessons Learned Related to PRBs Using a Funnel and Gate Configuration

The following is a summary of lessons learned from the 14 projects included in the report.

PRB Configuration

- For the Former Manufacturing Site, the funnel and gate PRB configuration was selected over other PRB configuration and remedial approaches to accommodate the buildings, railroad tracks, and public walkways on site, as well as adjacent public areas and properties. At that site, large areas were not accessible for excavation or other invasive remedial approaches

PRB Installation Method

- For the Federal Highway Administration Facility states that fractured aquitard materials and groundwater chemistry were important considerations that affected the performance of the remediation. Permeation infilling of the basal claystone was required, as well as a better geochemical awareness of the groundwater chemistry, to prevent groundwater flow under the barrier and to appropriately design the reactive zone.
- At the Intersil Semiconductor Site, a low permeable "wing" that extends perpendicular from the treatment wall to approximately 20 feet downgradient was installed to reduce the impact on groundwater velocity through the wall due to variations in regional directions of the flow.

- At the Fry Canyon site, the use of premixed bentonite slurry for construction of the no-flow barriers was problematic because it proved difficult to control the slurry used to construct the wing wall from migrating into the area intended for the gate structure.
- At the Y-12 Site, the use of guar in the construction of the PRB led to an unexpected increase in biological activity in the system, which improved contaminant degradation.

PRB Installation Depth

- At Area 5 at Dover AFB, the innovative caisson-based installation technique was used successfully to install the reactive media in a relatively deep aquifer. Caisson-based installation was required at Dover AFB because conventional excavation techniques that use a standard backhoe or clamshell were not feasible because of the greater depth of the aquifer and the presence of underground utilities.

Reactive Media Used

- In addition to helping distribute flow through the PRB, the pea gravel zone placed upgradient of the PRB at the Intersil Semiconductor Site resulted in the precipitation of naturally occurring minerals and partial treatment of target chemicals upgradient of the iron treatment zone. According to site managers, the life of the treatment zone was expected to be extended even though there was the potential negative effect of mineral precipitation.
- The results of a tracer study conducted on the Former Mill Site PRB showed that, while groundwater generally moved in a straight path through the system, some unexpected lateral groundwater flow was observed, where an increase in residence time may have increased the contaminant degradation within the PRB reactive zone.
- One of the reactive gates in the Area 5 Dover Air Force Base PRB used iron preceded by a 10% pyrite and sand mixture that served to moderate the pH of the reactive bed, thereby decreasing the precipitates formed. In addition, the use of pyrite resulted in control of pH levels within the reactive zone.
- For the East Garrington site the gate of the PRB was aerated using air-sparging techniques, which enhanced biodegradation through the addition of oxygen to the treatment cell. However, experiments demonstrated that using an Oxygen Release Compound in the reactive zone of the PRB was not effective.
- For the Fry Canyon Site, site managers anticipated that if remediation using the PRBs were to continue at the site, the following could affect the long term performance of these barriers: the long term release of PO_4 sorbed to iron rich sediments in the colluvial aquifer after removal of the PRB, and carbonate and sulfide mineral precipitation in the iron barrier.

Project Performance

- For the Federal Highway Administration Facility there was some evidence, based on decreases in calcium and inorganic carbon in the treated groundwater, of the presence of mineral precipitate (calcite and siderite) in the cells. The decreases were estimated to result in a potential loss of porosity of 0.5% per year of operation.
- At the Fry Canyon Site, the discovery of unexpected bedrock topography after the PRB was installed explained some of the suboptimal performance characteristics that had been observed. The *Installation Profile* states that, to prevent the problem from occurring in future PRB installations, a more detailed view of the bedrock topography is needed during site characterization activities.
- Seasonal hydraulic mounding was observed above the PRB installed at the Intersil Semiconductor Site. However, the *Installation Profile* states that the mounding was not expected to affect long-term performance of the barrier because affected groundwater was contained onsite when mounding was present and, when the mounding dissipated, groundwater flowed through the barrier and was treated.
- Performance data for the PRB installed at the Vapokon Petrochemical Work site showed that daughter products (DCA and DCM), were not expected to be degraded by the PRB, but were being degraded in the anoxic plume. The reduction of BTEX concentrations may have resulted from microbial reactions coupled to abiotic reactions.
- The *Installation Profile* for the Fry Canyon Site states that numerous hydrologic and water-quality characteristics will factor in to the selection of an appropriate point of compliance well when installing a PRB for groundwater remediation, and that quantification of groundwater flow is critical during pre-installation characterization and after PRB emplacement.

Project Cost

- The projects ranged in total cost from \$67,200 (East Garrington Site) to \$1,000,00 (Federal Highway Administration Facility, Intersil, and the Y-12 Sites) from It is likely that additional matrix characteristics and operating parameters, such as soil classification; clay content and/or particle size distribution; pH; porosity; depth below ground surface or thickness of zone of interest; total organic carbon; the presence of non aqueous phase liquid (NAPL); groundwater flow rate; and type of reactive media may also directly or indirectly factor in to project cost. However, because of the dissimilarities between the sites profiled in the report, more significant conclusions regarding costs to install and operate a funnel and gate PRB could not be made.
- During installation of the East Garrington PRB, an unexpectedly high water table complicated the construction of the trench, increasing installation costs; but not maintenance costs.

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Analysis Preparation

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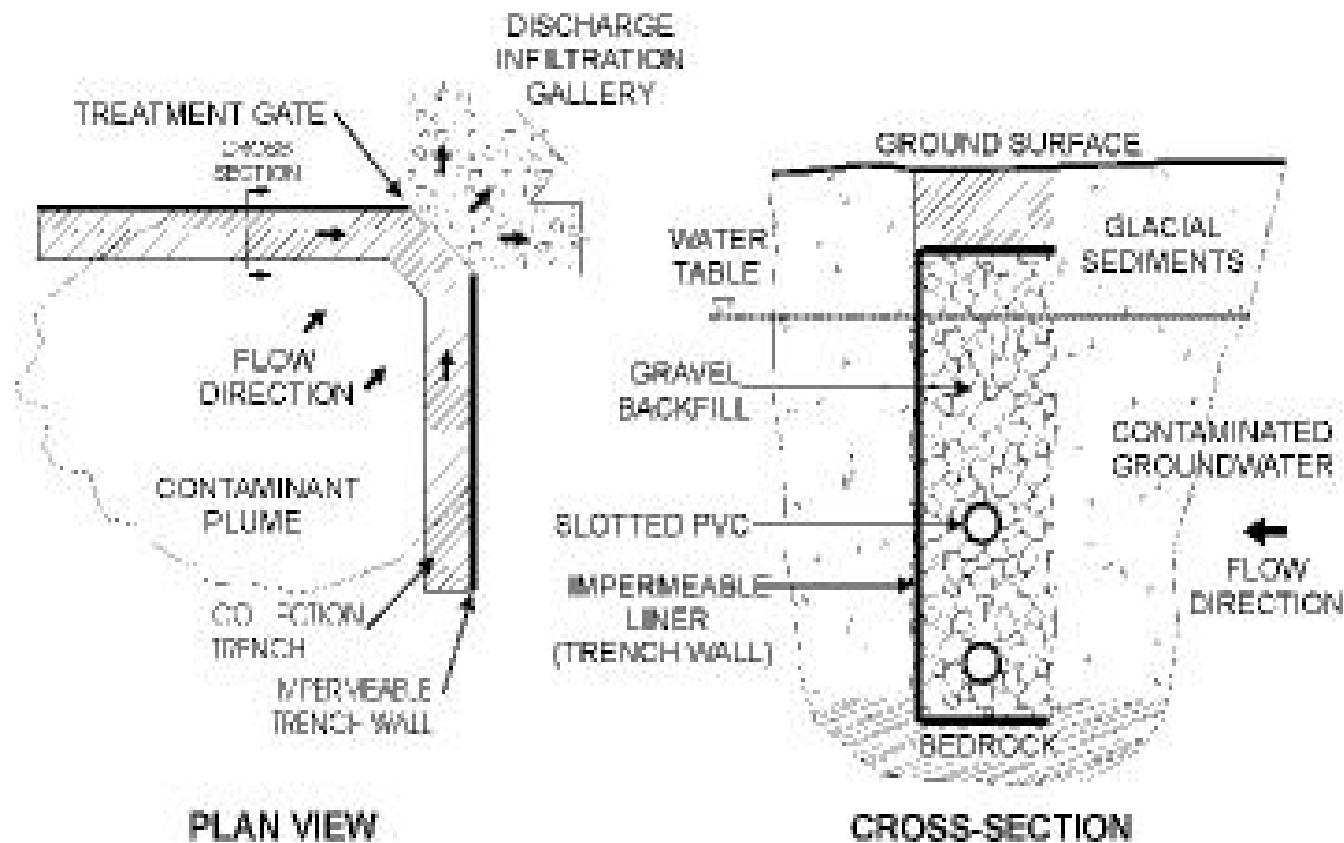
Table 1
Permeable Reactive Barriers Using a Funnel and Gate Configuration
Project Summary Information

Site Name and Location	Year Installed	Construction Method	Funnel Dimensions (Length and Maximum Depth)	Gate Dimensions (Length and Maximum Depth)	Gate Reactive Media	Contaminants	Installation Cost (Design Cost)
Full-Scale Applications – Chlorinated VOCs							
Aircraft Maintenance Facility, Southern Oregon, Oregon	1998	Continuous trenching/ supported excavation	650 ft long; 34 ft bgs	2 gates: (1) 50 ft long, (2) 60 ft long; both 34 ft bgs	2 gates: (1) iron, (2) iron and sand	TCE	\$600,000
Federal Highway Administration Facility, Lakewood, Colorado	1996	Supported excavation	1,040 ft long; depth not specified	4 gates: each 40 ft long; depth not specified	Iron	TCA; 1,1-DCE; TCE; cDCE	\$1,000,000
Former Manufacturing Site, Seattle Washington	1999	Supported excavation	330 ft long; 35 ft bgs	2 gates: each 45 ft long; both 34 ft bgs	Iron and sand	PCE, TCE, cis-DCE, VC	\$350,000
Industrial Site, Coffeyville Kansas	1996	Not provided	490 ft long; 30 ft bgs	20 ft long; 30 ft bgs	Iron	TCE; 1,1,1-TCA	\$300,000 (\$100,000)
Intersil Semiconductor Site, Sunnyvale, California	1995	Not provided	Not provided	36 ft long; 20 ft bgs	Iron	TCE; cis 1,2-DCE; VC; Freon113®	\$1,000,000
Vapokon Petrochemical Work, Sønderød, Denmark	1999	Supported excavation	400 ft long; 30 ft bgs	50 ft long; 30 ft bgs	Iron	PCE, TCE, TCA, DCA, DCE, DCM, BTEX	\$700,000 (\$240,000)
Pilot-Scale Applications – Chlorinated VOCs							
Alameda Point, Alameda, California	2000	Supported excavation	2 funnels 10 ft long; 24 ft bgs	15 ft long; 24 ft bgs	Iron and oxygen	cis 1,2-DCE; VC; TCE; BTEX	Not provided

Site Name and Location	Year Installed	Construction Method	Funnel Dimensions (Length and Maximum Depth)	Gate Dimensions (Length and Maximum Depth)	Gate Reactive Media	Contaminants	Installation Cost (Design Cost)
Area 5, Dover AFB Dover, Delaware	1998	Supported excavation	Funnel dimensions not specified	2 gates: each 8 ft long; both 45 ft bgs	Iron	PCE, TCE, DCE	\$800,000
Lowry AFB, Colorado	1995	Supported excavation	2 funnels 14 ft long; 17 ft bgs	10 ft long; 17 ft bgs	Iron	TCE	\$530,000
Moffett Federal Airfield, Mountain View, California	1996	Continuous trenching	2 funnels 20ft long; depth not specified	6ft long; depth not specified	Iron	TCE; cis 1,2-DCE; PCE	\$365,000 (\$175,000)
Full-Scale Applications – Other Contaminants							
Former Mill Site, Monticello, Utah	1999	Supported excavation	2 funnels 240 ft long and 97 ft long; 1 ft into bedrock	100 ft long; 1 ft into bedrock	Iron	U, As, Mn, Se, V	\$800,000
Pilot-Scale Applications – Other Contaminants							
East Garrington, Alberta, Canada	1995	Supported excavation	2 funnels 145 ft long; 16 ft bgs	3 gates in series, each 6 ft long; 16 ft bgs	Oxygen	BTEX	\$67,200
Fry Canyon Site, Fry Canyon, Utah	1997	Not provided	Funnel dimensions not specified	Three gates, 7 ft long each; 4 ft bgs	Iron, AFO, PO ₄	U	\$140,000 (\$30,000)
Y-12 Site, Oak Ridge National Laboratory, Oak Ridge, Tennessee	1997	Supported excavation	2 PRBs: (1) 220 ft long; 25 ft bgs and (2) 225 long; 30 ft bgs	2 PRBs: (1) concrete vault and (2) 26 ft long; 30 ft bgs	Iron	U, Tc, Nitric Acid	\$1,000,000

Figure 1

Schematic Diagram of the Funnel and Gate at the East Garrington Site



Note: Best quality available

Source: RTDF

Permeable Reactive Barrier Project Profile: Aircraft Maintenance Facility, Southern Oregon, OR

Installation Year: 1998
Contaminants: Trichloroethene
Reactive Media: Iron
Cost: \$600,000
Construction: Funnel and Gate
Point of Contact: Dave Weymann
EMCON Associates
15055 SW Sequoia Pkwy
Suite 140
Portland, Oregon 97224
Telephone: (503) 624-7200
Facsimile: (503) 620-7658
Email: dweymann@emconinc.com

A full-scale demonstration of a permeable reactive barrier (PRB) to remediate groundwater contaminated with trichloroethylene (TCE) was installed in March 1998 at an aircraft maintenance facility in southern Oregon. Historical use of chlorinated solvents for degreasing purposes resulted in the groundwater contamination by TCE and other degradation compounds. Total volatile organic compound (VOC) concentration in the upper aquifer encountered at the site was approximately 500 micrograms per liter ($\mu\text{g/L}$).

The site is underlain by heterogeneous alluvial deposits ranging from sandy silts to silty gravels. At a depth of 24-34 below ground surface (bgs) is a fine-grained aquitard. The depth to the water table varies seasonally between 4 and 8 ft bgs. Average hydraulic conductivity for the alluvial deposits is 3 ft/day.

The funnel-and-gate system consists of two gates, each 50 ft wide, and a 650-ft-long funnel. The funnel walls are composed of a 2-ft-thick soil-bentonite slurry installed to the top of the aquitard with a hydraulic conductivity of 0.0003 ft/day. The first gate is composed of two layers, each 50 ft wide and 9 in thick, consisting of 100% zero-valent iron filings. Both layers were installed using a continuous trencher, then connected to the funnel by driven sheet piles. The second gate, upgradient from the first, is 3 ft wide, 60 ft long, and composed of mixed sand and iron filings. It was installed with a trackhoe and drag box.

Four monitoring wells, two upgradient and two downgradient, have been installed for each gate. Sampling began in April 1998. Current plans call for sampling every two months for four periods and then quarterly for the foreseeable future.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project.

Permeable Reactive Barrier Project Profile: Federal Highway Administration Facility, Lakewood, CO

Installation Year: 1996
Contaminants: Trichloroethane, 1,1-Dichloroethene, Trichloroethene, cis-Dichloroethene
Reactive Media: Iron
Cost: \$1,000,000
Construction: Funnel and multiple gate
Point of Contact: J. H. Woll
Federal Highway Administration
555 Zang Street
Room 259
Lakewood, Colorado 80228
Telephone: (303) 716-2106
Facsimile: (303) 969-5903
Email: jhwoll@road.cflhd.gov

A permeable reactive barrier (PRB) system was installed in October 1996 at a site in Lakewood, Colorado. Contaminants at the site included 1,1,1-trichloroethane (TCA), 1,1-dichloroethylene (1,1-DCE), trichloroethylene (TCE), and cis-dichloroethylene (cDCE). Design concentrations for the PRB include TCE and 1,1-DCE concentrations up to 700 µg/L. No information is provided on the concentrations of cis-DCE or (TCA).

The contaminated area is an unconfined aquifer that is 15-25 ft thick and consists of unconsolidated gravelly sand overlying weathered (fractured) claystone. These units are in hydraulic connection and act as one aquifer. The geometry of the aquifer is irregular, with a local presence of clay lenses in the unconsolidated sand and sandstone lenses in the claystone. The aquifer is confined from below by unweathered (unfractured) claystone. No information is provided on porosity, transmissivity, hydraulic conductivity, etc.

The PRB system is comprised of a 1,040-ft funnel section and four reactive gate sections, each 40 ft wide. This was the first funnel and multiple gate PRB system using granular zero-valent iron. A high degree of lateral geologic heterogeneity and variation in volatile organic compound (VOC) concentrations led to varying iron thicknesses in each gate. The gates were constructed using a sheet pile "box." Native material was excavated from the box and the reactive material installed, separated from the aquifer materials by a layer of pea gravel.

The cost of the PRB system was about \$1,000,000. This includes the cost of design, construction, materials, and the zero-valent iron.

Groundwater velocities through the gates were expected to range from 1 ft/day to 10 ft/day, depending upon the hydrogeologic conditions in the vicinity of the respective gates. Measurements in the cells using a heat-pulse flowmeter have ranged from < 0.1 ft/day to about 1.5 ft/day. Design concentrations include up to 700 µg/L of TCE and 700 µg/L of 1,1-DCE. Half-lives of about 1 hour or less were measured for these compounds in bench-scale design studies. The only VOC exiting the cells above the 5 µg/L reporting level is 1,1-dichloroethane, which has been measured up to 8 µg/L on the downgradient side of the cells. There is some evidence of the precipitation of calcite and siderite in the cells based on decreases in calcium and inorganic carbon in the treated groundwater. This is estimated to result in a potential porosity loss of 0.5% of the porosity per year of operation.

Hydraulic head has increased upgradient of the barrier, with up to 10 ft of head difference measured across the barrier. This increases the possibility for contaminated water to move around the barrier. Indeed, VOC concentrations are increasing in groundwater moving around the south end of the barrier and there is some evidence of VOCs moving under the barrier in one location.

Lessons Learned

Fractured aquitard materials and groundwater chemistry have greatly affected this remediation attempt. Permeation infilling of the basal claystone is required along with geochemical awareness of the groundwater chemistry.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project.

Permeable Reactive Barrier Project Profile: Former Manufacturing Site, Seattle, WA

Installation Year: 1999
Contaminants: Tetrachlorethene, Trichloroethene, cis-Dichloroethene, Vinyl Chloride
Reactive Media: Iron filings
Cost: \$350,000
Construction: Funnel and Gate
Point of Contact: Barry Kellems, P.E.
Hart Crowser, Inc.
1910 Fairview Ave. East
Seattle, Washington 98102-3699
Telephone: (206) 324-9530
Facsimile: (206) 328-5581
Email: barry.kellems@hartcrowser.com

A full-scale permeable reactive barrier (PRB) system was installed at a former manufacturing site in Seattle, WA in 1999. The funnel and gate PRB was selected to accommodate the buildings, railroad tracks, and public walkways on site, as well as adjacent public areas and properties, which precluded large excavations for remediation. The 200 ft wide groundwater plume consisted of tetrachloroethylene (PCE) and its degradation products trichloroethylene (TCE), cis-1,2-dichloroethylene (cis-DCE), and vinyl chloride (VC). Two potential source areas were identified with the maximum detected constituent concentrations in groundwater of 50 mg/L PCE, 23 mg/L TCE, 8 mg/L cis-DCE, and 0.8 mg/L VC. Areas of high pH (up to pH 12) were also found in the groundwater.

The site was used for metal anodizing and light manufacturing from the 1940s until 1989. It sits within 200 ft of the Lake Washington Ship Canal and adjacent to the third most popular tourist destination in the city. Upper soil layers consisted of heterogeneous fill material overlaying stratified estuarine deposits, forming two distinct water-bearing zones. Chlorinated solvents were found up to 32 ft deep beneath the surface where a dense, relatively impermeable till prevents vertical migration of contaminants.

The 330 ft long funnel and gate consists of three cement bentonite (CB) cutoff walls (funnels) and two 45 ft long permeable reactive gates. The 3 ft wide gates were designed with a 50/50 mixture of iron filings and sand. Approximately 180 tons of iron were used. The gates were constructed with biodegradable, guar--based slurry, thus avoiding the cost of and need to drive sheet piling. The barrier was embedded 3 ft into the dense, impermeable till layer to prevent underflow. The total depth of the wall ranged from 24-35 ft.

Each of the funnels was constructed by excavating under CB slurry. Within days the CB hardened to a clay-like material that is relatively impermeable. It was able to withstand various obstructions including sewer pipes, a water line, and railroad tracks. The gate sections were constructed by excavating under a bio-polymer slurry composed of guar gum, additives and water. Two temporary wells were installed in each gate. An iron and sand mixture was piped directly into the trench under the slurry. After backfilling, the temporary wells were pumped while adding breaker enzymes, and recirculating the slurry over the top of the iron/sand. This caused the slurry to degrade without the need for disposal. After a few days of recirculating, the viscosity of the bio-polymer was reduced and the trench was ready for a final cap of compacted clay. The total installation cost including construction and materials was approximately

\$300,000. Design costs were \$50,000 including the pilot test. An additional \$50,000 was spent on site preparation and restoration and soil disposal.

Due to the proximity to the Ship Canal, the cleanup goals for treatment were based on protection of surface water, specifically 4.2 µg/L PCE, 56 µg/L TCE, 80 µg/L c-DCE, and 2.9 µg/L VC. Six months after installation, the measured treatment efficiencies for the wall were 65% for c-DCE, 95% for VC, and greater than 99% for both PCE and TCE. Natural attenuation processes down gradient of the wall, including intrinsic biodegradation, are reducing concentrations to below surface water cleanup standards before reaching the canal. Quarterly monitoring continues at the site.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project. Included in the online profile are photographs of the PRB installation for the site.

Permeable Reactive Barrier Project Profile: Industrial Site, Coffeyville, KS

Installation Year: 1996
Contaminants: Trichloroethene, 1,1,1-Trichloroethane
Reactive Media: Iron
Cost: \$400,000
Construction: Funnel and gate
Point of Contact: Greg Somermeyer
ThermoRetec Corporation
23 Old Town Square
Suite 250
Fort Collins, Colorado 80524
Telephone: (970) 493-3700
Facsimile: (970) 493-2328
Email: gsomermeyer@thermoretec.com

This permeable reactive barrier (PRB) system was installed at the property boundary of an industrial site in Coffeyville, KS, in January 1996. The site covers about 200 acres and is hydrologically and geochemically complex. Contaminants include trichloroethylene (TCE) and 1,1,1-trichloroethane (TCA). Prior releases at this site had generated a dissolved plume approximately 875 yds long contaminated with 400 µg/L of TCE and 100 µg/L of 1,1,1-TCA. Contaminant transport occurred to the greatest lateral extent in a basal sand and gravel unit just above shale bedrock, which lies about 30 ft beneath the site. There is nearby public use of shallow groundwater, necessitating measures to prevent additional off site migration.

Shale bedrock located about 30 ft below the ground surface is overlain by sand and gravel unit. No Information.

The PRB system uses a funnel-and-gate configuration to direct groundwater through a single, permeable treatment gate that is 20 ft long and 3 ft thick. The funnel section of the system consists of two 490-ft soil-bentonite slurry walls on either side of the treatment gate. Zero-valent iron is used as the reactive material. The treatment wall contains 70 tons of the iron. A low groundwater flow velocity of 0.2 ft/day permitted the use of this relatively high funnel-to-gate ratio. The system is installed to a depth of 30 ft in a basal alluvial aquifer.

The installation cost for the system, including slurry walls, treatment gate, and granular iron, was approximately \$400,000.

No determinations of groundwater velocity through the system have been made to date. Concentrations in the iron zone are below maximum contaminant levels (MCLs).

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project.

Permeable Reactive Barrier Project Profile: Intersil Semiconductor Site, Sunnyvale, CA

Installation Year: 1995
Contaminants: Trichloroethene, cis-Dichloroethene, Vinyl Chloride, Freon 113®
Reactive Media: Iron
Cost: \$1,000,000
Construction: Funnel and gate
Point of Contact: Carol Yamane
Geomatrix Consultants, Inc.
100 Pine Street
San Francisco, California 94111
Telephone: (415) 434-9400
Facsimile: (415) 434-1365
Email: cyamane@geomatrix.com

In 1995, after being approved by the California Regional Water Quality Control Board, a permeable reactive barrier (PRB) was installed at the Intersil Semiconductor Site in Sunnyvale, CA. Intersil had manufactured semiconductors at the site from the early 1970s until 1983. In 1972, the company had installed a concrete, epoxy-lined, in-ground system at the facility to neutralize acid in wastewater before discharge to a sanitary sewer. Soil and groundwater contamination from halogenated volatile organic compounds (VOCs) was identified near the neutralization holding tank site after it was removed early in 1987. Initial concentrations of contaminants were 50-200 µg/L of trichloroethylene (TCE), 450-1,000 µg/L of cis-1,2-dichloroethylene (cDCE), 100-500 µg/L of vinyl chloride (VC), and 20-60 µg/L of Freon 113®. Groundwater extraction and treatment, using an air stripper, began late in 1987. The in situ PRB system replaced the existing pump-and-treat system, which was being maintained at a significant cost. The original system has been removed and the property has been restored to full economic use. The monitoring wells provide access to the in situ system for periodic monitoring compliance.

The contaminated area is in a semiconfined aquifer that is 2-4 ft thick. It is composed of interfingering zones of silty, fine-grained, fine- to medium-grained sand, and gravelly sand. The geometry of the aquifer is irregular, with a local presence of clay lenses. The aquifer is mostly confined by an upper silty-clay and clay layer, which ranges from 9-12 ft thick, and by a lower aquitard of clay and silty clay, which is about 65 ft thick.

The physical constraints of the site helped determine the geometry of the PRB and the construction technique used. To address historically changing groundwater flow directions, low permeability walls were installed upgradient and perpendicular to the PRB to contain affected groundwater onsite prior to flow through the barrier. The treatment zone is sandwiched between permeable gravel layers to evenly distribute flow through the zone. The barrier itself is 4 ft wide, 36 ft long, and 20 ft deep. It is charged with 220 tons of granular iron (Fe⁰) to a depth of about 11 ft. A low, permeable "wing" that extends perpendicular from the treatment wall to about 20 ft downgradient was installed to reduce the impact on groundwater velocity through the wall due to variations in regional flow direction.

Installation cost for the in situ PRB system, including the slurry walls used to direct groundwater toward the permeable reactive barrier, was \$1,000,000. This includes the cost of construction, materials, and the iron. Design cost for this system is not available.

The cleanup goal established for the site is to reduce contaminant concentrations to levels below the Maximum Contaminant Level (MCL) set by the State of California and Primary Drinking Water Standards—5 µg/L for TCE, 6 µg/L for cDCE, 0.5 µg/L for VC, and 1,200 µg/L for Freon 113[®]. Since installation, VOC concentrations have been reported below cleanup goals from monitoring wells located within the iron wall. While seasonal hydraulic mounding has been observed above the PRB, it is not expected to affect long-term performance of the barrier. Affected groundwater is contained onsite when mounding is present. When the mounding dissipates, groundwater again flows through the barrier and is treated.

Lessons Learned

In addition to helping distribute flow through the PRB, the pea gravel zone placed upgradient of the PRB has resulted in precipitation of naturally occurring minerals and partial treatment of target chemicals upgradient of the iron treatment zone. Some mixing of the iron into the pea gravel zone is likely to have occurred during construction and resulted in chemical conditions favorable for some mineral precipitation (for example, higher pH, lower redox potential than ambient groundwater). This is evidenced by inorganic chemistry data from wells within the pea gravel. While site managers did not anticipate this benefit, the result is expected to extend the life of the treatment zone relative to the potential negative effects of mineral precipitation.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project.

Permeable Reactive Barrier Project Profile: Vapokon Petrochemical Works, Sønderød, Denmark

Installation Year: 1999
Contaminants: Tetrachloroethene, Trichloroethene, Trichloroethane, Dichloroethane, Dichloroethene, Dichloromethane, Benzene, Toluene, Ethylbenzene, and Xylene
Reactive Media: Iron
Cost: \$940,000
Construction: Funnel and gate
Point of Contact: Peter Kjeldsen
Technical University of Denmark
Environmental & Resources DTU
Building 115
DTU, DK-2800
Kgs. Lyngby Denmark
Telephone: 45 45251561
Facsimile: 45 45932850
Email: pk@er.dtu.dk

A full-scale permeable reactive barrier (PRB) system was installed in 1999 to remediate groundwater at Vapokon Petrochemical Works, a solvents recycling factory, in Sønderød, Denmark. The factory used distillation and other processes to purify used solvents containing chlorinated aliphatic, mainly perchloroethylene (PCE), trichloroethylene (TCE), and benzene, toluene, ethylbenzene, and xylene (BTEX). The main spill area was an open underground concrete tank, from which the used solvents were transferred from drums. The unsaturated zone and aquifer contain mainly PCE, TCE, trichloroethane (TCA), 1,2-dichloroethane (DCA), dichloroethylene (DCE), dichloromethane (DCM), and BTEX. The maximum concentration of any single chlorinated compound is 5,000 µg/L. Groundwater chemistry in the plume is anoxic, probably the result of oxygen consuming compounds, such as BTEX.

The soil at the site contains a 12-ft layer of loam and soil fillings, below which is a water-saturated sandy aquifer approximately 30 ft thick. The clay layer below the aquifer has a minimal thickness of 50 ft. The groundwater flows toward a nearby rainwater pond at a velocity of 3.6-4.5 ft/day and from there to a creek.

The PRB system consists of a funnel and gate and was made using sheet piling. It contains a reactive zone of 105-yd³ Fe⁰ and 45 screens. The funnel is 400 ft long. The PRB is 50 ft long, 30 ft deep, and 2 ft thick. The basic PRB design was chosen mainly due to cost and the availability of construction techniques in Denmark. Because of the site's high -groundwater velocities, an upstream drainage system was incorporated into the design to reduce the natural -groundwater flow velocity through the PRB to about 1,300 ft/day. Leaking of the sheet piling, which occurred while constructing the PRB, led to expensive lowering of the -groundwater table and treatment of the pumped groundwater in granular activated charcoal filters. The design cost was \$240,000, and the installation cost was \$700,000.

Several wells and piezometers are used to monitor the removal efficiency of the barrier system. The wells were sampled in 2000 and analyzed for chlorinated compounds, including their degradation products, and for BTEX and inorganic components as well. Slug tests were used to evaluate the permeability of the aquifer and the barrier material.

The results showed that most compounds were degrading at expected rates and that the system was achieving the goal of decreasing concentrations of chlorinated solvents below 10 µg/L. In addition, concentrations of some daughter products (DCA and DCM), which were not expected to transform in the column, were low, probably because they were degrading naturally in the anoxic plume. The reduction of BTEX concentrations may have been due to microbial reactions coupled to abiotic reactions. They were not believed to be a result of the iron particles. The inorganic analysis showed a reduction in ionic strength of the water passing through the PRB.

Concentrations at the upgradient side of the PRB for the chlorinated compounds increased over time. This change may have been due to the lower -groundwater velocities introduced by the drainage system upstream of the site. Sampling will occur every six months in 2001 and probably once a year thereafter.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project. Included in the online profile are photographs of the PRB installation at the site.

Permeable Reactive Barrier Project Profile:

Alameda Point, Alameda, CA

Installation Year: 2000
Contaminants: Trichloroethylene, cis-Dichloroethylene, Vinyl Chloride, and Benzene, Toluene, Ethylbenzene, and Xylene
Reactive Media: Iron and oxygen
Cost: Information not available
Construction: Funnel and Sequenced Gate
Point of Contact: Mary Morkin
GeoSyntec Consultants
1500 Newwell Avenue
901 North Fifth Street
Suite 800
Walnut Creek, California 94596
Telephone: (925) 943-3034 Ext. 203
Facsimile: (925) 943-2366
Email: mmorkin@geosyntec.com

The second part of a pilot-scale demonstration of an in situ sequenced permeable reactive barrier (SPRB) for the remediation of chlorinated solvents and petroleum hydrocarbons was conducted at Alameda Point (formerly U.S. Naval Air Station Alameda) in Alameda, CA.

The initial phase of this demonstration, which had been conducted at Canadian Forces Base Borden, Ontario, Canada, evaluated three technologies for their ability to treat perchloroethylene (PCE), carbon tetrachloride, and toluene. The technologies were: (1) abiotic reductive dechlorination using zero-valent iron followed by oxygen releasing compound (ORC[®]) to promote aerobic biodegradation; (2) natural attenuation; and (3) a permeable nutrient injection wall, using benzoate to promote anaerobic biodegradation, followed by an aerobic (oxygen) biosparge gate for aerobic biodegradation. The Alameda demonstration used zero-valent iron followed by oxygen biosparging in a funnel and-gate system to remediate trichloroethylene (TCE); cis-1,2-dichloroethylene (cDCE); vinyl chloride (VC); and toluene, benzene, ethyl benzene, and xylene (BTEX). Total initial (upgradient) concentrations of chlorinated VOCs exceeded 100 mg/L, and toluene was found at levels of up to 10 mg/L. Historical air photos of the site indicate open disposal pits upgradient of the SPRB.

The shallow aquifer is composed of 22-24 ft of sandy artificial fill material that was hydraulically placed on bay silts and clays. Depth to groundwater ranges from 4 to 7 ft below ground surface. The hydraulic conductivity of the overlying sandy fill material is 0.057 ft/day (~21 ft/year). The underlying bay silts and clays are 15-20 ft thick and act as a confining unit.

During construction of the funnel-and-gate system, the artificial fill sand was excavated to the top of the confining bay mud unit. To prevent settling, a concrete pad (nominally 2 ft thick) was placed at the bottom of the excavation; the gate was then constructed on this base. The gate is 10 ft wide and 15 ft long. As groundwater passes through the gate it contacts the following media: about 18 in of coarse sand mixed with 5% zero-valent iron, 5 ft of zero-valent iron, a 3-ft pea gravel transition zone, a 3-ft biosparge zone, and a 2-ft pea gravel zone. The 10-ft funnels were placed on either side of the gate, perpendicular to the direction of water flow.

Between February 1997 and May 1998, two pumping wells were used to operate the system under controlled conditions. For a period of about 70 days, the system operated at a flux rate of

approximately 45 ft³/day to determine the maximum velocity it could process. At this velocity, breakthrough was observed in several downgradient monitoring points. Then, the system operated for about one year at a flux rate of approximately 12 ft³/day, more representative of conditions that would exist as a result of the funnel sections. Finally, the system was allowed to operate under natural gradient conditions.

The remedial objectives of the project generally were met, except with respect to cDCE and VC, with typical effluent concentrations of about 136 µg/L and 217 µg/L respectively. Retardation of the toluene or other hydrocarbons as a result of sorption to the granular iron precluded an assessment of petroleum hydrocarbon degradation. Breakthrough of cDCE and VC indicated that biodegradation (likely via aerobic oxidation) of these compounds was occurring in the biosparge zone. An estimated 66% of the VC and 30% of the cDCE was volatilized. Assessment of multilevel data showed excellent degradation (>91%) of the chlorinated organics using the granular iron at high influent concentrations (>100 mg/L total VOCs). At lower influent concentrations, almost complete degradation (>99%) was observed. The biosparge zone supported aerobic biodegradation of VC and cDCE, and by January 1998 remedial objectives were being met at the last set of sampling wells in the gate.

Results obtained to date suggest sparging rates in the biosparge zone should be minimized to reduce volatilization of contaminants from the water column. In addition, monitoring should continue so that long-term performance of the SPRB can be assessed.

The U.S. Navy has begun to operate the site. Current plans call for a hydraulic study to examine groundwater flow in the funnel-and-gate area and for monitoring to continue on a quarterly basis.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project.

Permeable Reactive Barrier Project Profile: Area 5, Dover Air Force Base, Delaware, DE

Installation Year: 1998
Contaminants: Tetrachloroethene, Trichloroethylene, Dichloroethylene
Reactive Media: Iron
Cost: \$800,000
Construction: Funnel and Gate
Point of Contact: Arun Gavaskar
Battelle
Environmental Restoration Department
505 King Avenue
Columbus, Ohio 43201-2693
Telephone: (614) 424-3403
Facsimile: (614) 424-3667
Email: Gavaskar@battelle.org

A pilot-scale field demonstration of a permeable reactive barrier (PRB) is being conducted at the Area 5 site at Dover AFB, DE. The demonstration is funded by the Strategic Environmental Research and Development Program (SERDP). The Dover site is contaminated with perchloroethylene (PCE), trichloroethylene (TCE), and dichloroethylene (DCE). The maximum concentrations encountered during site characterization were 5,617 µg/L of PCE, 549 µg/L of TCE, and 529 µg/L of DCE.

Area 5 lies within the Atlantic Coastal Plain Physiographic Province, consisting of Cretaceous to Recent sedimentary deposits of gravel, sand, silt, clay, limestone, marl, and chalk dipping to the southeast. Groundwater is located 5-15 ft below ground surface (bgs). The clay aquitard is located 40-45 ft bgs. The hydraulic conductivity values used for design of the permeable barrier were based on an aquifer conductivity range of 10-50 ft/day.

Major objectives of the demonstration include comparing two reactive media schemes and examining innovative emplacement techniques designed to reduce the cost of construction for PRB systems. The funnel-and-gate system, installed in January 1998, consists of two gates that are 8 ft wide and 45 ft deep. One gate is filled with pure, zero-valent iron filings with a 10% iron and sand pretreatment zone to stabilize flow and remove dissolved oxygen. The second gate also is filled with iron, but it is preceded by a 10% pyrite and sand mixture. The mixture serves to moderate the pH of the reactive bed, thereby decreasing the precipitates formed.

The gates were constructed with 8-ft-diameter caissons that were removed after reactive media emplacement. The funnel sections were built using Waterloo interlocking sheet piling driven to the 45-ft depth and keyed into the underlying clay aquitard.

The total cost for the system was \$800,000. This includes the cost of design, construction, materials, and the reactive material.

Following installation, the reactive and hydraulic performance of the PRB were evaluated primarily through two comprehensive monitoring events in July 1998 and June 1999. Limited monitoring events were conducted periodically throughout the demonstration to monitor specific operating parameters.

At the end of 18 months of operation, core samples of the gate and surrounding aquifer media were collected and analyzed for precipitate formation. Monitoring results showed that the PRB was functioning as designed in terms of capturing the plume and reducing the contaminants down to below target limits. The pretreatment zones (PTZ) in both gates succeeded in removing dissolved oxygen from the groundwater before it entered the reactive cell. In addition, the use of pyrite did result in some degree of pH control while the groundwater was in the PTZ of Gate 2. Magnesium, nitrate, and silica were the main inorganic species precipitating out of the low-alkalinity groundwater as it flowed through the gates.

The reactivity of the PRB was assessed in terms of the ability of the two reactive cells to degrade the influent chlorinated volatile organic compounds (CVOC) (PCE, TCE, and cis-1,2,-DCE) and their byproducts (cis-1,2,-DCE and VC) down to respective MCLs. CVOCs persisted longer in Gate 2 than in Gate 1. This is because the pyrite in the Gate 2 PTZ is not as strongly reducing as the iron, and does not promote reductive dechlorination to the same extent as iron. No CVOCs were detected in the exit zones in both gates. The maximum concentration discovered in the expected capture zone of the PRB is 3,900 µg/L of PCE. Evaluation of the residence time in the reactive cells and the capture zone of the PRB were the main objectives of the hydraulic performance evaluation. Results show the estimated range of residence times in each reactive cells is 1 to 9 days. This estimate is based on a representative range of gate velocities of 0.46 to 4.1 ft/day measure during the demonstration. Aquifer heterogeneities, differential packing of the media in the two gates, and fluctuations in groundwater flow volume and direction contribute to this relatively wide range of estimates. A relatively strong hydraulic gradient along the flowpath through both gates indicates that groundwater is being captured by the PRB. However, due to low hydraulic gradient in the upgradient aquifer, the size and orientation of the capture zone cannot be determined with certainty. In all probability, the capture zone is about 40 to 50 ft wide, an estimate based on the estimated range of flow velocities in the gates, the measured hydraulic gradients through the gates, and the measure water levels in the upgradient aquifer. The geochemical performance indicated the DO and ORP levels in the groundwater decline along the flowpaths, indicating that a strong reducing environment is created in both gates. The PTZ containing iron (Gate 1) was more efficient at removing DO than the PTZ containing pyrite (Gate 2). Very little precipitate buildup was observed in cores from both gates after 18 months of PRB operation. Available information is insufficient to make any conclusions about the long-term performance (i.e., longevity) of the PRB.

The demonstration is being used to validate the document "Design Guidance for Application of Permeable Barriers to Remediate Dissolved Chlorinated Solvents," developed with input from state and federal regulators and published in February 1997. The guidance document will be updated to reflect lessons learned at the completion of the project.

Lessons Learned

The innovative caisson-based installation technique was used successfully to install the reactive media in a relatively deep aquifer. Caisson-based installation was required at Dover AFB because conventional excavation techniques that use a standard backhoe or clamshell were not feasible at Dover due to the greater depth of the aquifer, presence of underground utilities, and higher cost.

Both reactive media in the PTZ of the gates were successful in their primary function of scrubbing out dissolved oxygen. However, once the water left the PTZ and entered the reactive cell, the tendency of the iron to raise the pH overwhelmed any pH control achieved by the pyrite.

Achieving pH control was desirable objective because low pH has the potential to reduce precipitation in the reactive cell and thus increase the longevity of the barrier.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project.

Permeable Reactive Barrier Project Profile: Lowry Air Force Base, Denver, CO

Installation Year: 1995
Contaminants: Trichloroethylene
Reactive Media: Iron
Cost: \$530,000
Construction: Funnel and gate
Point of Contact: William A. Gallant
Versar, Inc.
11990 Grant Street
Suite 500
Northglenn, Colorado 80233
Telephone: (303) 452-5700
Facsimile: (303) 452-2336
Email: gallabil@versar.com

A demonstration project of a permeable reactive barrier (PRB) to remediate groundwater contaminated with chlorinated hydrocarbons was initiated at Lowry Air Force Base, CO. Contamination at Lowry is a result of various base activities generating contaminants that were transferred to local groundwater via storm drains, septic tanks, or direct infiltration. The total chlorinated hydrocarbon concentration was approximately 1,400 µg/L, primarily consisting of trichloroethylene (TCE).

The Lowry site is underlain by unconsolidated alluvial deposits and artificial fill that is approximately 18 ft thick. These surficial deposits overlie bedrock consisting of silty claystones and sandy siltstones. The local water table aquifer is approximately 9 ft below ground surface (bgs) and saturates alluvial material as well as the upper 10 ft of underlying bedrock in places. Local groundwater flow patterns are partly controlled by paleochannels eroded into the underlying bedrock. Hydraulic conductivity for the site averages 35 ft/day, and the average groundwater velocity is 1 ft/day. The local water table aquifer is approximately 9 ft bgs and saturates alluvial material as well as the upper 10 ft of underlying bedrock in places. Local groundwater flow patterns are partly controlled by paleochannels eroded into the underlying bedrock.

The funnel and gate system constructed consists of a 10-ft wide and 5-ft thick reactive wall composed of 100% granular, zero-valent iron and two 14-ft sheet piling walls that were installed to a depth of 17 ft.

The total cost for the system was approximately \$530,000. This includes design, construction, materials, and the reactive material.

Thirty-four wells located within and proximate to the wall were used to monitor the system's performance. Seven sets of samples were taken from December 1995 through June 1996. Data analysis indicates that a first-order, abiotic reaction involving reductive dehalogenation is taking place within the reactive iron wall. Chlorinated hydrocarbons are being completely degraded within the first foot of the wall. After 18 hours residence time (2 ft into the wall), all analytes degrade to their respective analytical quantitation limits. In addition, intermediate breakdown products produced during the process are also degraded. The wall was resampled in May 1997 with similar results. Since the PRB was designed and built as a short-term solution, there are no plans to continue the monitoring.

During a clogging study performed in May 1997, 18 months after installation, calcite, ragonite, "green rusts", amorphous iron hydroxides, and magnetite were observed. A porosity loss of 9.7% for the 18-month operational period was estimated from the investigation.

A slurry wall containment area was constructed in October 1997 30-50 ft upgradient of the PRB as part of a new source area remedial system.

In September 1999, nine additional wells were installed upgradient of the wall, two continuous flow direction and velocity systems (Hydrotechnics) were installed and the wall was cored. The objective of the current investigation is to assess hydraulic conditions and longevity issues associated with the current wall conditions. The work was funded by the U.S. Department of Defense Environmental Security Technology Certification Program (ESTCP) and the Strategic Environmental Research and Development Program. The work is being performed by Battelle, assisted by Versar, Inc., under a contract with the Naval Facilities Engineering Service Center (NFESC) with the support of Air Force Center for Environmental Excellence (AFCEE), the U.S. Corps of Engineers (USACE), and Lowry AFB (AFBCA) personnel. Reports documenting the results of this activity are in progress.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project.

Permeable Reactive Barrier Project Profile: Moffett Federal Airfield, Mountain View, CA

Installation Year: 1996
Contaminants: Trichloroethylene, 1,2-Dichloroethylene, Tetrachloroethene
Reactive Media: Iron
Cost: \$540,000
Construction: Funnel and Gate
Point of Contact: Chuck Reeter
Naval Facilities Engineering Service Center
1100 23rd Avenue
Code 411
Port Hueneme, California 93043-4370
Telephone: (805) 982-0469
Facsimile: (805) 982-4304
Email: creeter@fesc.navy.mil

A pilot-scale permeable reactive barrier (PRB) was constructed in April 1996 at the former Naval Air Station (NAS) Moffett Field in Mountain View, CA, by the U.S. Navy Engineering Field Activity-West. Previous investigations identified extensive groundwater contamination on the site from dissolved chlorinated hydrocarbons—trichloroethylene (TCE), dichloroethylene (1,2-DCE), and perchloroethylene (PCE)—much of which originated offsite. Initial concentrations were 2,990 µg/L (TCE), 280 µg/L (1,2-DCE), and 26 µg/L (PCE) upgradient of the iron gate. The overall Moffett Field solvent plume is more than 10,000 ft long and about 5,000 ft wide.

Subsurface sediments at the Moffett Field PRB site are a mixture of alluvial-fluvial clay, silt, sand, and gravel. Sands and gravels are present as lens-shaped, interbraided channel deposits that are presumed to have incised into the clay and silt layers. Contamination is present in two aquifer zones that extend from 5 to 60 ft below ground surface (bgs). These aquifer zones are separated by a discontinuous, semiconfining clay layer (aquitard) at approximately 25 ft bgs, ranging from 1-15 ft in thickness. Average linear flow velocities from onsite pumping tests were calculated to be about 1-4 ft/day. Hydraulic conductivity values for the separating aquitard layer range from 10--5 feet/minute (ft/min) to 10--3 ft/min. Soil porosity values in the silts and sands ranged from 30-45%.

A funnel-and-gate system was installed in the upper aquifer zone to just above the aquitard using a trenching method. The system includes a reactive iron gate that is 10 ft wide by 6 ft long and contains about 75 tons of granular zero-valent iron. The iron cell is bounded by 2-ft sections of pea gravel at upgradient and downgradient locations. Two 20-ft-long steel sheet pile funnels or wing walls are positioned on either side of the reactive iron gate.

The cost of planning and design of the system was \$100,000. Installation cost, including construction, materials, and the reactive material, was approximately \$365,000. Bench-scale testing required another \$75,000.

The U.S. Department of Defense (DoD) Environmental Security Technology Certification Program (ESTCP) has sponsored the demonstration project at Moffett Field for the past three years. The Naval Facilities Engineering Service Center has collected performance monitoring and cost data to validate the PRB technology for potential use at DoD sites worldwide. Water quality sampling from 1996 (June and September) and 1997 (January, April, July, and October) from about 70 monitoring wells in or near the reactive barrier consistently have indicated

significant degradation of chlorinated compounds. All principal contaminant concentrations had been reduced to below Maximum Contaminant Levels (MCLs) or non-detectable levels within the first 2-3 ft of the gate (iron cell). Bromide tracer testing at the PRB site revealed that flow velocities through the cell are about 0.5-2 ft/day. The final PRB technology evaluation report for the Moffett Field pilot demonstration project was published in November 1998. A summary version was published in December 1998.

Lessons Learned

Coring results have suggested that conditions exist for potential long-term formation of chemical precipitates in the iron cell. This may lead to an eventual reduction in the longevity and efficiency (permeability and reactivity) of the reactive barrier. The DOD ESTCP, U.S. Environmental Protection Agency (EPA), and U.S. Department of Energy (DOE), in partnership with the RTDF Permeable Reactive Barriers Action Team, are sponsoring additional performance and longevity evaluations to support widespread regulatory acceptance and encourage use of PRB technology. As part of these efforts to further investigate the potential concerns for biological fouling and chemical precipitation, annual water quality sampling and iron cell coring are planned at several PRB sites across the country, including Moffett Field, over the next three years.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project. Included in the online profile are links to 2 websites with additional information on this site:

<www.nfec.navy.mil>

<www.epa.gov/radiation/cleanup/documents>

Permeable Reactive Barrier Project Profile:

Former Mill Site, Monticello, UT

Installation Year: 1999
Contaminants: Uranium, Arsenic, Manganese, Selenium, Vanadium
Reactive Media: Iron
Cost: \$800,000
Construction: Funnel and gate
Point of Contact: Don Metzler
U.S. Department of Energy
2597 B 3/4 Road
Grand Junction, Colorado 81503
Telephone: (970) 248-7612
Facsimile: (970) 248-6040
Email: d.metzler@gjo.doe.com

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2597 B 3/4 Road
Grand Junction, Colorado 81503
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Email: s.morrison@gjo.doe.com

A full-scale permeable reactive barrier (PRB) was installed in 1999 to remediate groundwater at a Superfund site in Monticello, UT. Cleanup of this site is being managed by the U.S. Department of Energy (DOE) Grand Junction Project Office, in cooperation with U.S. EPA Region 8 and the State of Utah. The former Monticello mill site was built in 1942. It was operated as a uranium and vanadium ore-processing mill intermittently until 1960. Major groundwater contaminants of concern at the site are uranium (U), selenium (Se), vanadium (V), manganese (Mn), and arsenic (As). These contaminants were present at initial concentrations of 700 µg/L, 40 µg/L, 400 µg/L, and 10 µg/L, respectively.

The site occupies a 110-acre tract on the southeast edge of Monticello. When the mill was closed, approximately 2.3 million yd³ of low-level radioactive mill tailings, contaminated soil, and other miscellaneous debris remained on site.

The funnel-and-gate system includes slurry walls that funnel the contaminated plume through the gate, a PRB containing zero-valent iron (Fe⁰). The south slurry wall is 240 ft long and the north wall is 97 ft long. These funnel walls are composed of a bentonite and soil slurry mix. The barrier was built by driving steel sheet piling into the bedrock forming a rectangular box approximately 100 ft long by 8 ft wide. The native soils inside the box were replaced with Fe⁰ and gravel packs upgradient and downgradient of the Fe⁰. The Fe⁰ and gravel packs extend more than 1 ft into the underlying bedrock aquiclude. The upgradient gravel pack is approximately 2 ft wide and is composed of 13% to -4/+20 mesh Fe⁰ (by volume) mixed uniformly with 0.5 in gravel. The center section of the barrier contains 4 ft of 100% -8/+20 mesh Fe⁰. The downstream gravel pack is approximately 2 ft wide composed of 0.5-inch gravel and includes an air-sparging system constructed of perforated polyvinyl-chloride pipe. The air sparging system is being used to remove dissolved manganese and iron if the concentrations increase to unacceptable levels. Installation of the system cost \$800,000.

An extensive monitoring network was installed to evaluate the performance of the PRB. To date, nine sampling rounds have been completed (September, October, and November 1999; and January, April, August, and October 2000; January and April 2001). Additional comprehensive sampling will be conducted in July 2001 and then a reduced number of wells and analytes will be evaluated on a quarterly basis in the future.

Overall, the PRB wall has been effective in reducing contaminant concentrations. Concentrations of As, Se, U, and V have been reduced to non-detectable levels within the PRB. As expected, concentrations of iron increase as groundwater passes through the PRB. Concentrations of iron exiting the wall are lower than expected (based on the treatability studies) and are well within acceptable risk ranges. Additional data evaluation is ongoing to make more accurate estimates of groundwater velocities and residence times in the gate.

Lessons Learned

An extensive tracer study, conducted in July 2000, showed that groundwater moved through the reactive gate at a rate of 2.4 to 18 ft/day; the design velocity was 10 ft/day. While groundwater generally moved in a straight path through the system, some groundwater moved laterally through the Fe⁰ before it moved downgradient.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project. Included in the online profile is a link to a website with additional information on this project:
<www.gjo.doe.gov>

Permeable Reactive Barrier Project Profile: East Garrington, Alberta, Canada

Installation Year: 1995
Contaminants: Benzene, Toluene, Ethylbenzene, and Xylene
Reactive Media: Oxygen
Cost: \$67,200
Construction: Trench and gate
Point of Contact: Marc Bowles
Komex International, Ltd.
16th Avenue, NW
Suite 100
Calgary, Alberta T3B 0M6 Canada
Telephone: (403) 247-0200
Facsimile: (403) 247-4811
Email: mbowles@calgary.komex.com

A pilot-scale permeable reactive barrier (PRB) was installed at the East Garrington gas plant in Alberta, Canada in September 1995. Initial concentrations of up to 12 mg/L of BTEX (benzene, toluene, ethylbenzene, and xylene) were detected. The gas processing plant was contaminated by condensate, lube oil, flare pit wastes, and other materials. The goal of the pilot-scale demonstration was to contain the BTEX on site and ensure that only treated groundwater migrated off site.

The site is underlain by 10-16 ft of low-conductivity glacial till composed of silty clay and cobble-rich deposits that grade into a clay-rich sandy to silty basal unit. This is underlain by a silty shale with occasional interbedded sandstone units. The contaminated aquifer extends from the near the surface to 10 ft below ground surface (bgs). No information is given on porosity, transmissivity, hydraulic conductivity, etc.

Two 145-ft long cutoff trenches were excavated at right angles to each other through the fine-grained glacial sediments down to the relatively impermeable bedrock. The bottom and the downgradient sides of the trenches were then sealed with an impermeable, synthetic liner before being filled with highly permeable aggregate. The PRB system consists of three 6-foot wide modular treatment gates in series. They were constructed of vertical culverts that inject air into the contaminated groundwater, which promotes hydrocarbon degradation. The residence time inside the treatment gate is approximately 24 hours. The treated groundwater then passes through an infiltration gallery composed of thin vertical trenches filled with highly permeable gravel.

The cost of the system was approximately \$67,200. This includes design, construction, and materials.

A passive permeable reactive barrier was chosen as a remedy for the site because of its low maintenance costs, despite the longer timeframe required for remediation. More specifically, a trench-and-gate system was selected over a funnel-and-gate system because of its advantages in low permeability sediments such as glacial tills. Compared with traditional standalone barriers, the combination of a cut-off wall and adjacent drainage trench (1) improves drainage of the contaminated zone; (2) increases the size of the capture zone both horizontally and vertically; and (3) prevents damming effects such as mounding which force contaminants around or under funnel walls.

Results of the pilot-scale project show that the contaminant plume has been captured and treated by the trench-and-gate system. Recent sampling yielded BTEX concentrations below 10 µg/L at the treatment gate, and no contaminants have been detected off site. Monitoring equipment includes soil moisture sensors, tensiometers, and pressure transducers installed upgradient, downgradient, and along the trench. Experiments conducted in the system using artificially contaminated water suggest that total BTEX concentrations up to 2.5 mg/L can be effectively treated. Sampling will continue on a biannual basis.

Lessons Learned

During installation, an unusually high water table led to trenching problems. The high water table increased installation costs, but had no effect on maintenance costs.

Air sparging was found to be an effective method for enhancing biodegradation through the addition of oxygen to the treatment cell. Experiments using Oxygen Releasing Compound were not effective. However, the addition of phosphorus increased degradation rates.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project. Included in the online profile is a schematic diagram of the PRB installed at the site.

Permeable Reactive Barrier Project Profile: Fry Canyon Site, Fry Canyon, UT

Installation Year: 1997
Contaminants: Uranium
Reactive Media: Iron, Amorphous Ferric Oxide, Phosphate
Cost: \$170,000
Construction: Funnel and gate
Point of Contact: David N. Naftz, Ph.D.
U.S. Geological Survey
1745 W. 1700 South
Salt Lake City, Utah 84104
Telephone: (801) 975-3389
Facsimile: (801) 975-3424
Email: dlnaftz@usgs.gov

A field-scale demonstration of a permeable reactive barrier (PRB) system is underway at an abandoned uranium upgrader site in Fry Canyon, UT. EPA is the lead agency on the site. The ultimate goal of the demonstrations is to determine the technological and economic feasibility of using permeable chemical or biological obstacles, placed in the flow path, for removing dissolved metals and radionuclides from contaminated groundwater. This project is testing the performance of three permeable reactive barriers at the Fry Canyon site. Anticipated results of the research for each of the PRBs tested will include long-term removal efficiencies for uranium and an evaluation of the commercialization potential for each. Specific objectives of the field demonstration project include: (1) hydrologic and geochemical characterization of the site prior to emplacement of barriers; (2) design, installation, and operation of three PRBs; and (3) evaluation of barrier(s) performance and commercialization potential.

At the Fry Canyon site, the water table is located approximately 8 ft to 9 ft below ground surface, and the underlying aquifer ranges from 1 ft to 6 ft deep. Estimated hydrologic properties and measured hydraulic gradients indicate that groundwater in the alluvial aquifer moves at a rate of about 1.5 ft/day nearly parallel to the direction of stream flow. The uranium (U) concentration in the shallow colluvial aquifer ranges from 60 µg/L in water from a background well to 20,700 µg/L in water beneath the tailings. The hydraulic conductivity of the barriers is approximately 1,500 ft/day, while that of the surrounding native material is 1 to 2 orders of magnitude smaller. Native material consists poorly sorted fine- and medium-grained sand.

The funnel and gate system, installed in August 1997, is comprised of three barriers, each constructed of different reactive materials. One is bone char phosphate (PO₄), another is foamed zero-valent iron (Fe⁰) pellets, and the third is amorphous ferric oxide (AFO). Each barrier is approximately 7 ft wide, 3 ft thick, and 4 ft deep. Approximately 110 ft³ of material was used in each barrier. Each contains 22 monitoring points, a water-quality mini-monitor, four pressure transducers, and a flow-sensor port. According to steady-state modeling results, groundwater velocities in the reactive walls are about 4.5 ft/day.

The EPA and U.S. Geological Survey have estimated that the design cost (engineering design and planning for the funnel and gate construction) for this system totals \$30,000. The installation cost, including construction, materials, and the reactive materials, totals \$140,000. These estimates do not include bench-scale testing of the candidate barrier materials.

Sampling continues at the site. The last sampling event was in November 2000. Overall, results indicate that PO₄ and ZVI PRBs are still removing > 99% of the incoming uranium, but the AFO PRB has reached chemical breakthrough, which impacts the long-term performance capability of the barrier. A 50% breakthrough in the AFO PRB after about 1,000 pore volumes had been processed.

If remediation using the PRBs continues at the site, two additional problems are anticipated that could affect the long-term performance of these barriers: long-term release of PO₄ sorbed to iron-rich sediments in the colluvial aquifer after PRB removal, and carbonate and sulfide mineral precipitation in the ZVI barrier.

Results from early in the operation of these barriers showed that the input uranium concentrations differed significantly for each PRB, ranging from less than 1,000 mg/L in the PO₄ PRB to higher than 20,000 mg/L in the AFO PRB. The input uranium concentrations to each of the PRBs also varied seasonally by approximately 4,000 to 7,000 mg/L. During the first year of operation, the PRBs are removing the majority of incoming uranium; however, the percentage of uranium removal varied with time and barrier material. The ZVI PRB consistently removed greater than 99.9 % of the input uranium concentration in flowpath 1. The percentage of uranium removed in the PO₄ and AFO PRBs was slightly less than the ZVI PRB. Except for two monitoring periods, over 90% of the input uranium concentration was removed in the PO₄ barrier. The AFO PRB removed over 90% of the input uranium concentration through November 1997. From January 1998 through September 1998 the uranium removal percentage was reduced to less than 90%.

Lessons Learned

Several important lessons have been learned as a result of the Fry Canyon project. They include:

The uneven surface of the underlying confining unit made it difficult to ensure that each PRB gate structure or noflow barrier was in direct contact with the underlying confining unit. If either structure was placed on small lenses of the residual colluvial aquifer, this may have provided a pathway for contaminated groundwater to bypass the reactive material. A possible solution to prevent this would be the use of a more powerful track hoe that would be able to excavate into the underlying confining unit. This equipment would allow for a smooth surface and a gradient could be established that would drain the groundwater away during excavation, allowing the observation of the underlying confining unit. In addition, the use of pumps with a capacity exceeding the groundwater inflow will allow for visual inspections of the seal between the PRB and the confining layer.

The use of premixed bentonite slurry for construction of the noflow barriers was problematic. It was difficult to control the movement of slurry from the wing wall to the gate structure of each PRB. It is critical to know exactly where the bentonite slurry is. If the slurry flows into a gate structure it could impact the flow and treatment of contaminated groundwater in the finished PRB. In a worst-case scenario, the gate structure of the PRB could be sealed off, preventing the treatment of contaminated groundwater. A possible solution would be the use of non-hydrated bentonite chips for the construction of PRB wing walls and associated no-flow barriers. After placement, the chips would hydrate with the natural groundwater, ensuring correct placement during PRB construction. In addition, the use of bentonite chips would not require the added expense of cement mixers for slurry transport.

The placement of monitoring wells within the wing walls and other no-flow areas between PRB gate structures is important to ensure proper operation. Including these wells in the routine monitoring network can provide critical water-level and water-quality data useful in assessing PRB operation. For example, water levels measured in wing wall monitoring wells would be expected to respond more slowly to naturally occurring water-level increases observed within the PRB gate structures.

A large bedrock nose was encountered during PRB installation that resulted in a re-orientation of the PRBs. This re-orientation resulted in the entry of groundwater at an oblique angle into the PRB gate structures, rather than the perpendicular angle that was anticipated. In order to prevent this problem in future PRB installations, a more detailed view of the bedrock topography is needed during site characterization activities. Additional data on bedrock topography could be obtained by increased drilling density during pre-installation characterization activities or possibly by subsurface geophysical methods such as seismic or ground penetrating radar techniques.

During the pre-installation characterization, it is important to determine the amount of readily desorbable U contained in the contaminated aquifer sediments. In a remediation scenario where the source term is either removed or stabilized in place, the total mass of readily desorbed U will eventually pass through the PRB. Quantification of this mass is needed to properly design the contaminant removal capacity of the PRB prior to emplacement.

Numerous hydrologic and water-quality characteristics should be considered prior to the selection of an appropriate point of compliance (POC) well when installing a PRB for groundwater remediation. When a PRB is placed within the contaminant plume, the POC well should probably be placed within the PRB. If the POC well is placed downgradient of the PRB it is likely that contaminant free water exiting the PRB could become re-contaminated with readily desorbable contaminants from the aquifer sediments. For some PRB materials, such as ZVI, the placement of a POC well within the PRB could be problematic. For example, the high iron concentrations and high pH values of water within the Fry Canyon ZVI PRB may not meet water-quality compliance standards. However, if the POC wells were placed downgradient of the ZVI PRB, the high iron concentration and high pH values would be significantly reduced. In many situations the location of POC wells may have to be parameter specific depending on the barrier material and onsite hydrologic and geochemical conditions.

Quantification of groundwater flow during pre-installation characterization and after PRB emplacement is critical. This information is needed for PRB design and to monitor changes in PRB hydraulic conductivity after emplacement. Groundwater models provide adequate information to address barrier design issues during the pre-installation characterization phase. After PRB emplacement, tracer injection methods appear to be best suited for monitoring PRB performance over time. Results through 1999 at the Fry Canyon site indicated that in situ flow sensors are of limited use in monitoring changes in either groundwater flow or direction within PRBs. These data are still being evaluated.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project. Included in this online profile are links to two websites with additional information about this site:

<www.dutslc.wr.usgs.gov/fry>

<www.epa.gov/radiation/cleanup/documents>

Permeable Reactive Barrier Project Profile:

Y-12 Site, Oak Ridge National Laboratory, Oak Ridge, TN

Installation Year: 1997
Contaminants: Uranium, Technetium, Nitric Acid
Reactive Media: Iron
Cost: \$1,000,000
Construction: Funnel and gate, continuous trench
Point of Contact: Baohua Gu
Oak Ridge National Laboratory
Env. Sciences Division
Oak Ridge, Tennessee 37831-6036
Telephone: (423) 574-7286
Facsimile: (423) 576-8543
Email: b26@ornl.gov

Permeable reactive barrier (PRB) systems have been constructed in two different -groundwater pathways through the Y-12 site at the U.S. Department of Energy's (DOE) Oak Ridge National Laboratory, TN. Liquid wastes, including nitric acid (HNO_3) with uranium (U), and technetium (Tc), were placed in disposal ponds on the site from 1952 to 1981. The site was capped in 1983. Leached wastes have contaminated both groundwater and surface water.

The site is underlain by unconsolidated clay and regolith overlying fractured shales. The permeability of the clay is very low (approximately 4×10^{-7} in/sec), but the weathered bedrock above the shales generally has a higher permeability (locally as high as 4×10^{-4} in/sec). The depth to groundwater is 10-15 ft, and the shallow unconsolidated unit aquifer is 10-20 ft thick. The PRBs are focused on capturing groundwater in this shallow unconsolidated zone.

Pathway 1 PRB

A funnel and gate system was installed in the area designated Pathway 1 in December 1997. It is approximately 220 ft long and consists of two wing walls designed to funnel groundwater to a concrete vault containing treatment canisters for evaluating different treatment media. The treatment vault consists of five vertically stacked reactors. An advantage of vertical reactors is the ease of cleaning and replacing used or clogged iron. The wing walls were installed to a depth of approximately 25 ft. The natural groundwater gradient and permeability contrast between the gravel backfill in the trench and surrounding native silt and clay is designed to generate flow through the treatment zone. Barriers were installed using a guar gum slurry for support to reduce slumping in the trench. An enzyme breaker was used to digest the guar, which was recycled down the trench as construction progressed.

Pathway 2 PRB

A continuous trench system was installed in the area designated Pathway 2 in November 1997. It is 225 ft long, 2 ft wide, 22-30 ft deep, and filled with gravel except for a 26-ft section in the middle that is filled with 80 tons of zero-valent iron (Fe^0). Guar gum was added during excavation to keep the trench walls from collapsing. The trench was installed parallel to the direction of groundwater flow.

Although total iron and ferrous iron concentrations were initially high after installation, concentrations have decreased as the pH within the iron has increased over time (to as high as 9 or 10). This initial spike is likely a result of enhanced microbial activity from the guar used in the barrier installation. Due to the effect of the guar on groundwater chemistry, nitrate concentrations increased in the upgradient wells over time. Sulfate levels in the groundwater have decreased as sulfate is reduced to sulfide. Additionally, a decreased concentration of calcium in groundwater was observed and may be attributed to the precipitation of calcium carbonate within the iron barrier. Continued monitoring and performance evaluation is in progress to better understand the flow paths through the PRB, the potential for clogging due to mineral precipitation, and the long-term effectiveness for uranium removal.

The total cost for the two walls was approximately \$1,000,000. This includes the cost of design, construction, materials, and the reactive material.

The goals of the project were to investigate the feasibility and effectiveness of passive in situ treatment systems to remove the contaminants in the groundwater that are migrating to Bear Creek from the disposal ponds. Early results indicate that the Fe^0 is an efficient and cost-effective method of simultaneously removing certain radionuclides, such as U and Tc, as well as HNO_3 . Sampling to monitor performance is occurring on a monthly basis.

Lessons Learned

Pathway 1 PRB:

The use of guar increased biological activity in the system.

Pathway 2 PRB:

Preliminary evaluation of hydraulic and chemical data suggests that, under wet-season hydraulic conditions, contaminated groundwater may migrate across the trench instead of down the trench as designed. Vertical gradients at the site appear to have a significant impact on groundwater flow and capture. The data suggest that to effectively operate passively in all hydraulic conditions, the trench needs to be longer and discharge at a lower hydraulic head downgradient. The following modifications are planned for the Pathway 2 PRB in fiscal year 1999 to enhance treatment efficiency:

- 1) The trench will be extended an additional 100 ft to increase the groundwater capture zone.
- 2) Guar will not be used to excavate the trench extension because of potential geochemical impacts on the iron, media, native soil, and groundwater observed during initial trench construction.
- 3) Groundwater from the trench extension will be siphoned approximately 800 ft to a second Fe^0 treatment zone deployed in subsurface concrete boxes.
- 4) The treated water will flow into an infiltration trench downgradient of the second treatment zone.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project. Included in the online profile is a photograph of the PRB installation at the site.